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(54) Rotary transformer.

(57) A rotary transformer (100) with an annular stator (102) and rotor (104) each having a generally U-shaped transverse section which are axially interdigitated in closely spaced arrangement. The stator has the primary coil (114) wound on the radially outer surface of the inner leg of its U-shape; and, the rotor has the secondary coil (116) wound on the inner surface of the radially outer leg of its U-shape. The primary coil is optimized at 10 turns of winding; and, the secondary coil has about 40 turns for maximizing secondary current output at frequencies of 2-5 kHz. The transformer is optimized by an iterative design procedure to give maximum power output per unit volume and per unit mass.

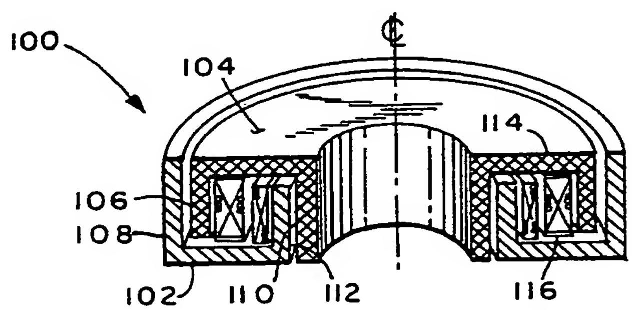

FIG. 1

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BACKGROUND OF THE INVENTION

The present invention relates to transformers of the type having the primary and secondary coils disposed for relative rotation such as for example where one or the other of the coils is mounted to a stationary structure and the other coil is mounted on a shaft or tube disposed for rotation concentrically with respect to the stationary coil. Heretofore, rotary transformers have been employed for transmitting low level signals across a rotary junction for example in torque or rotary displacement transducers. Devices of this sort are employed for providing a low level position or strain indicating signal generally for measurement or providing a control signal and have not heretofore been employed where it was desired or necessary to transmit any significant amount of power across such a rotary junction in a non-contact arrangement.

In certain automotive applications as for example user operated control switches on a vehicle steering wheel and for providing power to energize an airbag inflater mounted on the steering wheel, it has been the practice heretofore to employ slip rings or a spirally wound ribbon conductor to provide electrical contact across the rotary junction between the steering column and the steering shaft. Slip rings have the disadvantage that where an foreign matter can degrade the electrical contacting surfaces, spirally wound ribbon conductors have the disadvantage of requiring an expensive link of conductive material and requiring complicated and difficult assembly procedures when the steering wheel is installed in the vehicle.

Thus it has been desired to provide a way or means of providing a noncontact rotary electrical junction which can transmit both signal level and significant power level signals thereacross in a manner which is low in manufacturing cost and high in reliability.

Referring to FIG. 15, a prior art transformer is indicated generally at 10 as having a rotatable shaft 12 disposed centrally within annular stator members 14,16. A plastic rotor 18 is attached to the rotating shaft 12. A stator member having a generally U-shaped configuration is denoted by reference numeral 20 and has a coil 28 wound on the inner surface of the outer leg thereof and has a second stator member 22 disposed axially adjacent thereto. Rotor 18 has a rotating coil 30 mounted thereon for rotation with respect to coil 28.

SUMMARY OF THE INVENTION

The present invention provides a rotary transformer having annular stator and rotor magnetically permeable members having a generally U-shaped transverse section which has the legs of the U-shape interdigitated in an axial direction with the primary and secondary coils wound respectively on the adjacent legs of the U-shaped sections. The transformer of the present invention has the primary coil mounted on the radially outer periphery of the inner leg of the U-shaped stator member; and, the secondary or output coil is wound on the inner surface of the radially outer leg of the U-shaped rotor member. The transformer is particularly adapted for an automotive steering column application wherein the stator is mounted to the stationary column and the rotor is mounted to the steering shaft which passes therethrough. The transformer is designed by an iterative process which optimizes the turns ratio and the amount of iron or ferromagnetic material to provide relatively high efficiency in the frequency range 2-5 kHz. The transformer provides uniquely high power transmitting capabilities per unit of volume and per unit mass at the frequencies mentioned. The transformer of the present invention is particularly suitable for transmitting signals from user actuated control buttons mounted on a steering wheel, such as those for radio operation or cruise control functions across the rotary steering column-shaft junction. The transformer of the present invention is also uniquely suitable for transmitting power level signals at near saturation levels for firing an ignitor squib to inflate a vehicle occupant restraint airbag mounted on the vehicle steering wheel.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an isometric section view of the transformer of the present invention;

FIG. 2 is an enlarged cross-sectional view of the transformer of FIG. 1;

FIG. 3 is a schematic of the magnetic reluctances of the transformer of FIG. 1;

FIG. 4 is a Thevenin equivalent of the circuit of FIG. 3;

FIG. 5 is a further Thevenin equivalent of the circuit of FIG. 4

FIG. 6 is a plot of the power output in watts as a function of the number of secondary turns for various values of primary turns of the transformer of FIG. 1

FIG. 7 is a plot of the power output in watts as a function of the number of secondary turns for various values of frequencies for the transformer of FIG. 1;

FIG. 8 is a plot of primary current in amps as a function of the number of secondary turns at various frequencies for the transformer of FIG. 1;

FIG. 9 is a plot of primary current in amps as a function of the number of secondary coil turns for various numbers of primary coil turns for the transformer of FIG. 1;

FIG. 10 is a plot of power output in watts normalized for volt amperes in the primary as a function of frequency for the transformers of FIG. 1 and the prior art;

FIG. 11 is a plot of power output in watts per gram of transformer weight as a function of excitation frequency for the transformer of the present invention in the upper plot and the prior art in the lower plot;

FIG. 12 is a plot of power output in watts per cubic centimeter transformer volume as a function of excitation frequency with the upper graph representing the present invention and the lower graph representing the prior art;

FIG. 13 is a plot of power output in watts per cubic centimeter transformer volume as a function of excitation frequency at saturation flux densities with the upper plot representing the present invention and the lower plot the transformer of the prior art;

FIG. 14 is a graph of power output in watts per gram transformer weight as a function of excitation frequency plotted at saturation flux densities with the upper graph representing the present invention and the lower graph the prior art; and,

FIG. 15 is a cross-section of a prior art transformer.

DETAILED DESCRIPTION

Referring to FIG. 1, the transformer of the present invention is indicated generally at 100 and has an annular ferromagnetic stator member 102 having a generally U-shaped configuration in cross-section with the radially outer leg having a slightly greater axial extent than the radially inner leg of the U-shape.

An annular ferromagnetic rotor member 104 is disposed in concentric relationship with stator 102; and, rotor 104 has a generally U-shaped configuration in cross-section with the legs thereof interdigitated axially with the legs of the U-shape of stator 102. The outer leg 106 of the U-shape of the rotor is disposed closely spaced adjacent the outer leg 108 of the U-shaped stator; and, the inner leg 110 of the rotor is spaced closely adjacent the inner periphery of the inner leg 112 of the stator. A primary coil 114 is wound around the inner leg 112 of the stator; whereas, the output or secondary coil 116 is wound about the inner periphery of the outer leg 106 of the rotor.

The manner and technique for determining the physical parameters of the transformer of the present invention will now be described with reference to the drawings.

DESIGN PROCEDURE

Referring to FIG. 2
Choose H1 = K, a constant, all around
Assume D2, based on steering shaft diameter
Choose G1 = G2 = G3 = G4 = G5
Choose H5 based on Volume Constraints

I. FOR PRIMARY COIL

Assume N1 = 10 = Number of Coil Turns of Cu magnet wire
ASSUME WIRE SIZE = 20 awg
ASSIGN PRIMARY COIL PARAMETERS
p = packing factor for windings
D = D_4 = COIL I.D. (meters)
R = resistance of windings (Ohms)
ρ = resistivity of Cu = 1.7214×10^{-4} ohm - meters
H = COIL AXIAL LENGTH (meters) = H5 - G5 - 2(H1)
di = ϕ of wire with insulation (single varnish layer) (m)
de = ϕ of bare Cu wire (m)
a = cross sectional area of winding space (m^2)
MTL = Mean turn length of windings

$$compute: \; di = \frac{(.325)(.0254)}{(1.194^{AWG})} \; ; \; d_c = \frac{(.325)\,(.0254)}{(1.123^{AWG})}$$

$$a = \frac{\pi\, di^2}{4} \left(\frac{N}{p} \right) \; ; \; W = \frac{a}{H}$$

O.D. = D4 + 2W = Primary Coil O.D. (meters)
MTL = π (D + W)

$$R_1 = \rho \left[\frac{(N)\,(MTL) + 0.6}{\pi dc^2/4} \right]$$

II. FOR SECONDARY COIL
ASSIGN COIL PARAMETERS
ASSUME N_2 = 4N1 = NUMBER OF COIL TURNS
WIRE SIZE = 20 AWG
p = packing factor for windings
AWG = AMER. WIRE GAGE
D = O.D. + 2(G5) = COIL I.D. meters, where O.D. = Primary Coil O.D.
ρ = resistivity of Cu: 1.724 x 10^{-4} (ohm-meters)
H = COIL AXIAL LENGTH (meters) = H5 - G5 - 2(H1)
Compute
di, dc, a, W, MTL, R_2 as was done for primary coil
D5 = D + 2W = Coil O.D. (meters)
Referring to FIGS. 2, 3 and 4 determine reluctances
Reluctance of MEMBER A = R_A

$$R_A = \frac{l}{\mu A} = \frac{H5 - (H1 + G2)}{\mu \left(\frac{\pi}{2} \right) (D4 + D3)} = \frac{(H5 - H2)}{\mu \frac{\pi}{2} (D4 + D3)}$$

Where μ = permeability of ferrite material and is in the range

$$\mu = (2.9 - 7.2)10^{-3} \frac{Tesla \;\; meters}{ampere \;\; turn}$$

Reluctance of MEMBER E = R_E

$$R_E = \frac{l}{\mu A} = \frac{\frac{(D5 - D2)}{2}}{\mu \frac{\pi}{2} (D5 + D_2)\, H1} = \frac{D5 - D2}{\mu\, \pi\, (D5 + D_2) H1}$$

Reluctance of GAP 1 = R_{G1}

$$R_{G1} = \frac{Gap\ Size}{Gap\ Area} \times \left(\frac{1}{\mu_o}\right) = \frac{G1}{\mu_o}\left[\frac{1}{\pi\left(\frac{D3+D2}{2}\right)(H5-H1)}\right]$$

$$Where\ \mu_o = permeability\ of\ air = 4\pi \times 10^{-7}\ \frac{Tesla\ meters}{ampere\ turn}$$

$$\therefore R_{G1} = \frac{2G1}{\mu_o\ \pi\ (D3+D2)\ (H5-H1)}$$

Reluctance of GAP 2 = R_{G2}

$$R_{G2} = \frac{Gap\ Size}{Gap\ Area} \times \left(\frac{1}{\mu_o}\right) = \frac{G2}{\pi}\ \frac{2}{\mu_o\ (D4+D3)\ (H5-H2)}$$

Reluctance of Member D = R_D

$$R_D = \frac{l}{\mu A} = \frac{H5}{\pi\ \mu\left(\frac{D2+D1}{2}\right)H1}$$

Reluctance of Member B = R_B

$$R_B = \frac{l}{\mu A} = \frac{\frac{(D7-D4)}{2}}{\mu\pi\left(\frac{D7+D4}{2}\right)H1} = \frac{(D7-D4)}{\mu\pi\ (D7+D4)\ H1}$$

Reluctance of Member C = R_C

$$R_C = \frac{l}{\mu A} = \frac{(H5)}{\mu\pi\left(\frac{D8+D7}{2}\right)H1} = \frac{2}{\mu\pi\ (D8+D7)H1}$$

Reluctance of GAP 4 = R_{G4}

$$R_{G4} = \frac{Gap\ Size}{Gap\ Area}\left(\frac{1}{\mu_o}\right) = \frac{(H4 - H3)}{\mu_o\ \pi\left(\frac{D6 + D5}{2}\right)H1} = \frac{2\ (H4-H3)}{\pi\ \mu_o\ (D6 + D5)H1}$$

Reluctance of Member F = R_F

$$R_F = \frac{l}{\mu A} = \frac{H3}{\mu\ \pi\ H1\left(\frac{D5 + D6}{2}\right)} = \frac{2\ H3}{\mu\ (\pi)\ (D5 + D6)H1}$$

Referring to FIG. 4

$$R_{COMBINED_{G1,\,D,\,G2}} = \frac{R_{G2}\ (R_{G1} + R_D)}{R_D + R_{G1} + R_{G2}}$$

$$R_{COMBINED_{C,G3G4}} = \frac{R_{G4}\ (R_C + R_{G3})}{R_C + R_{G3} + R_{G4}}$$

Referring to FIG. 5

$$RM = \sum_i R_A + R_{COMBINED_{G1,D,G2}} + R_E + R_B + R_{COMBINED_{G,G3G4}} + R_F$$

$$R_{L1} = \frac{1}{P_{L1}} = \textit{Leakage reluctance for primary coil}$$

$$\textit{Where } P_{L1} = 4\mu_o \int_{R_i}^{R_O} \left(\frac{R_i}{r} + 1 \right) dr = 4\mu_o R_i \left[ln\left(\frac{R_O}{R_i} \right) + \left(\frac{R_O - R_i}{R_i} \right) \right]$$

$$\textit{Where } R_i = \frac{D4}{2} \; ; \; R_o = O.D._1$$

$$R_{L2} = \frac{1}{P_{L2}} = \textit{Leakage reluctance for secondary coil, where}$$

$$P_{L2} = 4 \mu_o \int_{R_i}^{R_O} = \left(\frac{R_i}{r} + 1 \right) dr = 4\mu_o R_i \left[ln\left(\frac{R_O}{R_i} \right) + \left(\frac{R_O - R_i}{R_i} \right) \right], \textit{ where}$$

$$R_i = \frac{ID_2}{2} \; ; \; R_O = \frac{D5}{2}$$

Referring to FIG. 5.

1.

$$V_1 = N_1 \times \frac{d\phi_1}{d\,t} + I_1 \times R_1$$

2.

$$V_2 = N_2 \frac{d\phi_3}{dt}$$

2(a) $Z_2 = R_2 + R_L - X_L$; *where* $X_L = O$ *for resistive loads*

2(b)

$$KR = \frac{R_{L1} + R_{L2} + RM}{R_{L2}}$$

3.

$$N_1 \times I_1 - N_1^2 \times \frac{d\phi_1}{dt} + V_1 \times \frac{N_1}{R_1}$$

4.

$$N_2 \times I_2 = \frac{N_1^2}{Z_2} \times \frac{d\phi_3}{dt}$$

5. $NI \times I_1 - (\phi_1 - \phi_2) \times RL_1 = O$

6. $RL_1 \times (\phi_2 - \phi_1) + RM \times \phi_2 + RL_2 \times (\phi_2 - \phi_3) = O$

7. $RL_2 \times (\phi_3 - \phi_2) + N_2 \times I_2 = O$

8.

$$AA \times \frac{d^2\phi_1}{dt^2} + BB \times \frac{d\phi_1}{dt} + CC \times \phi_1 = DD \times \frac{dV_1}{dt} + EE \times V_1$$

$$\text{where } AA = KR \times \frac{N_2^2}{Z_2} \times \frac{N_1^2}{R_1 \times R_{L1}}$$

$$BB = N_2^2 \times \left(KR - \frac{RL_1}{RL_2} \right) + (KR - 1) \times \frac{N_1^2 \times RL_2}{R_1 \times RL_1}$$

$$BB = N_2^2 \times \left(KR - \frac{RL_1}{RL_2} \right) + (KR - 1) \times \frac{N_1^2 \times RL_2}{R_1 \times RL_1}$$

$$CC = KR \times RL_2 - RL_1 - RL_2$$

$$DD = \frac{N_2^2 \times N_1 \times KR}{Z_2 \times R_1 \times RL_1} \; ; \; EE = (KR - 1) \times \frac{N_1 \times RL_2}{RL_1 \times R_1}$$

Since V_1 is a sinusoidal voltage, it may be assumed ϕ_1 is of the form.
9. K_1, $\sin \omega t + K_2 \cos \omega t = \phi_1$ where ω is the frequency of V_1.
Differentiating equation 9, expressions for

$$\frac{d\phi_1}{dt} \text{ and } \frac{d^2\phi_1}{dt^2}$$

are obtained, which, when substituted into equation 8 enable K_1 and K_2 to be determined from the conditions when alternately $\sin \omega t = O$ and $\cos \omega t = O$. Having obtained K_1 and K_2, equation 9 is then solved for ϕ_1.

With ϕ_1, determined, equation 1, is then solved for I_1. Having determined I_1, equation 5. is then solved for ϕ_2. The expression for ϕ_2 is then substituted into equation 6, which is solved for ϕ_3. Having obtained ϕ_3, equation 4, may then be solved for the secondary or output current I_2, by substituting for Z_2 from 2(a). Also, from equation 2, V_2, the transformer secondary, or output voltage is determined by differentiating and substituting for

$$\frac{d\phi_3}{dt}.$$

Using the above procedure, by choosing a load impedance and values for the transformer dimensions in FIG. 2, and choosing values for N_1, N_2 the values of V_2 and I_2 may be computed. In the present practice, the secondary coil load was assumed to have a purely resistive nature with a value of 2.5Ω. (Ohms) such as would be encountered in an electric firing squib. N_1 was incremented from 10 to 100 turns of #20 AWG copper; and, N_2 was incremented from 10 to 100 turns of #20 AWG copper. The input voltage V_1 was assumed to be 5 volts peak (3.5 VRMS) sinusoidal and the frequency ω of V_1 incremented from 100 Hz to 50 kHz.

Referring to FIG. 6, the above equations were solved for secondary voltage and current operating against a 2.5 ohm resistive load at an assumed frequency of 2 kHz with the gaps G1 through G5 having a common value of .030 inches (.762 millimeters) with D1 equal to one inch (25.4 millimeters) and H5 equal to .70 inches (17.8 millimeters) and the power output to the load was computed for increments of primary coil turns N1 in the range 10-100 for various values of the secondary turns N2 ranging from 10-100. The results are plotted as a family of curves for each increment of 10 turns of the primary winding plotted for values of secondary turns N2 versus power output to the load in watts. It will be seen from FIG. 6 that the predicted power output of the chosen configuration of the transformer of FIGS. 1 and 2 is maximized for the primary coil having ten turns and a secondary coil having the turn count N2 in the range 28-40. From the plots of FIG. 6 it was obvious that the configuration would be optimal if the ten turn primary coil were employed and the ratio of secondary turns to primary turns having a value of 4 were employed.

Referring to FIG. 7, the same physical transformer configuration having a primary coil of ten turns with the number of secondary turns N2 incremented from 10-100 was again entered into the above equations 1-8; and, the secondary voltage and current computed for incremented values of primary voltage frequency in the range of 100 Hz through 50 kHz. The results of these calculations are plotted as a family of curves for each frequency increment in FIG. 7, with the power output of the secondary into the 2.5 ohm resistive load plotted as a function of the incremented number N2 of secondary turns. It will be seen from FIG. 7 that at frequencies above one kHz the number of secondary turns should be in the range 4-5 times that of the number of primary turns in order to obtain optimum power output.

Referring to FIG. 8, the primary current I1 is plotted as a function of the number of secondary turns N2 as a family of curves for the various incremented values of frequency in the range 100 Hz through 50 kHz. It is seen from the various plots in FIG. 8 that for a frequency of 2 kHz or above, optimum results are achieved with at least 40 turns N2 of a secondary coil.

Referring to FIG. 9, a frequency of 2 kHz was chosen for the assumed transformer configuration and equations 1-8 were employed to compute the primary current I1 for various incremented values of the primary coil turns N1 in the range 10-100. The results are plotted as a family of curves in FIG. 9. It is also seen from FIG. 9 that for a primary coil turn count N1 of 10, a secondary coil turn count N2 of 40 provides near optimum results with a sufficient margin below saturation.

Thus the choice of 10 turns for the primary coil with a secondary coil turn count of 40 is considered in the presently preferred practice to achieve overall optimum results.

TABLE I

INVENTION								PRIOR ART					
weight (g)	341							102.6					
volume (cc)	83.36							16.88					
# primary turns	10							439					
# secondary turns	40							368					
primary resistance (ohms)	0.181							68.5					
secondary resistance (ohms)	0.611							18					
saturation flux density (Teslas)	.480							.300					
ACTUAL TEST DATA								ACTUAL TEST DATA					
All at 3.5 VRMS primary													
2.5 ohm load													
Frequency (Hz)		VAin (RMS)	P out (W)	FREQ	EFFICIENCY RATIO	WATTS/G	WATTS/CC	VAin (RMS)	P out (W)	FREQ	EFFICIENCY RATIO	WATTS/G	WATTS/CC
100	Saturated	48.83	8.469	100	0.173438	0.024836	0.101596	0.133	0.00378	100	0.028421	3.69E-05	0.000239
1000		32.57	12.116	1000	0.371999	0.035531	0.145346	0.121	0.00378	1000	0.03124	3.69E-05	0.000239
2000		28.458	10.221	2000	0.359161	0.029974	0.122613	0.099	0.00259	2000	0.026162	2.53E-05	0.000153
5000		19.08	4.248	5000	0.222642	0.012457	0.05096	0.057	0.00084	5000	0.014737	8.2E-06	5.29E-06
All at saturation flux densities	LINEAR SIMULATION ANALYSIS							LINEAR PROJECTION					
2.5 ohm load													
Frequency (Hz)		VAin (RMS)	P out (W)	FREQ	EFFICIENCY RATIO	WATTS/G	WATTS/CC	VAin (RMS)	P out (W)	FREQ	EFFICIENCY RATIO	WATTS/G	WATTS/CC
100		21.48	3.689	100	0.171741	0.010818	0.044254	N/A	0.132	100	N/A	0.001288	0.008312
1000		758	279.1	1000	0.368208	0.818475	3.348129	N/A	1.08	1000	N/A	0.010537	0.06401
2000		1884	631.3	2000	0.335085	1.85132	7.573177	N/A	1.04	2000	N/A	0.010148	0.065491
5000		4918	1087	5000	0.221025	3.187683	13.03983	N/A	1.1	5000	N/A	0.010732	0.06327

Referring to Table 1, a transformer having the above described dimensions was built and determined to have an overall weight of 341 grams and a volume of 83.4 cubic centimeters with a 10 turn primary and 40

turn secondary. The transformer secondary was connected to 3.5 VRMS excitation on the primary coil and with a 2.5 ohm resistive load connected across the secondary coil, the transformer was operated at various primary voltage frequencies incremented from 100 to 5 kHz and the power output to the load measured. The transformer was found to be substantially saturated with the primary voltage having a frequency of 100 Hz and the saturation flux density was determined to be 4800 gauss with 48 volt amperes RMS applied to the primary. The volts amperes applied to the primary and the output power were measured and the values are indicated in Table 1. The efficiency ratio, watts output per volt amperes input, was computed and the values are indicated in Table 1. Similar tests were conducted and measurements taken for the prior art transformer shown in FIG. 15; and, these values are also given in Table 1. In FIG. 10, the values of the efficiency ratio for the transformer of the present invention are plotted for the incremented frequencies of the excitation voltage as the upper plot with the measured values indicated by the black squares. Similarly, the values of efficiency ratio for the incremented excitation frequency of the input voltage are plotted as the lower plot with measured values indicated by the black diamonds in FIG. 10 for the prior art transformer. It will be seen from comparing the upper and lower plot of FIG. 10 that the efficiency of the transformer of the present invention in frequency ranging from 1-2 kHz is on the order of seven times the efficiency of the prior art transformer.

Based upon the test data and the physical measurement data presented in Table 1, computations were made for the power output of the transformer of FIG. 1 and the prior art transformer illustrated in FIG. 9. The results of these computations are listed in Table 1 as watts per gram weight and watts per cubic centimeter volume based upon the power output measured at the incremented values of input power frequency. The values have been plotted and are presented graphically in FIG. 11 where the upper plot with the calculated points indicated by black squares represents the values for the transformer FIG. 1; and, the lower plot with the computed values indicated by black diamonds represents the plot for the prior art transformer of FIG. 15. It will be seen that the power density expressed as watts output in the secondary coil N2 as a function of the transformer weight for the present invention is three orders of magnitude greater than the transformer of FIG. 15.

Referring to FIG. 12, the results of the computations of the output power of the transformer of FIG. 1 and FIG. 15 are presented in graphical form where the upper plot having the computed values shown in black squares represents the transformer of FIG. 1; whereas, the lower plot having the computed values illustrated in black diamonds represents the prior art transformer of FIG. 15. It will be apparent from FIG. 12 that the output power as a function of the volume of the transformer of FIG. 1 is three orders of magnitude greater than that of the prior art transformer of FIG. 15. For an excitation voltage of 5 volts peak or 3.5 volts RMS.

Referring to FIG. 13, the power output of the transformer of FIG. 1 has been computed by linear simulation analysis, at saturation flux densities for incremented values of frequency and plotted as watts per cubic centimeter volume as a function of frequency with the computed points shown as black squares in the upper plot of FIG. 13. The computed points are based on the data given in Table 1.

Referring to FIG. 14, the data for power output at saturation flux densities at incremented values of frequency was determined from Table 1 for the transformer of the present invention and plotted as a function of watts output per gram of transformer weight for the various incremented values of frequency which are indicated by black squares in the plot of FIG. 14. It will be seen by comparing FIG. 13 with FIG. 12 and FIG. 14 with FIG. 11 that the performance of the transformer of FIG. 1 is improved by driving the transformer to saturation.

The present invention thus provides heretofore unobtainable power output and efficiency per unit volume and per unit mass of a rotary transformer. The transformer of the present invention employs a unique interdigitated stator and rotor iron and coils which employ a U-shaped transverse configuration to the stator and rotor iron enabling the substantially higher output over a broader spectrum of frequencies than has been heretofore obtainable.

Although the invention has been hereinabove described with respect to the illustrated embodiment, it will be understood that the invention is capable of modification and variation and is limited only by the scope of the following claims.

Claims

1. A transformer for transmitting electrical power across a rotary junction comprising:
   (a) a primary stator (102) formed of ferromagnetic material having an annular configuration with a generally U-shaped configuration in radial section;

(b) a secondary rotor (104) formed of ferromagnetic material having an annular configuration with a generally U-shaped configuration in radial section, with the legs of said U-shape of said rotor and stator interdigitated in an axial direction;
(c) a primary coil (114) having its axis of winding coincident with the axis of said annular stator and received on one of the legs (112) of said stator U-shape;
(d) A secondary coil (116) having its axis of winding coincident with the axis of said annular rotor and received on one of the legs (106) of said U-shaped rotor with said secondary coil disposed at a common axial station with said primary coil; wherein the radially inner and outer legs of said stator and rotor U-shape define, respectively, and inner and outer radial air gap for magnetic flux between the stator and rotor, wherein said stator and rotor are disposed for relative rotation therebetween.

2. The transformer defined in claim 1, wherein said primary coil is received on the radially outer periphery of the radially inner leg of the U-shaped stator.

3. The transformer defined in claim 1, wherein said secondary coil is received on the radially inner periphery of the radially outer leg of the U-shaped rotor.

4. The transformer defined in claim 1, wherein said secondary coil has a multiple of four times the number of turns as the primary coil.

5. The transformer defined in claim 1, wherein said primary coil is wound on a bobbin.

6. The transformer defined in claim 1, wherein said secondary coil is wound on a bobbin.

7. The transformer defined in claim 1, wherein said U-shaped rotor and U-shaped stator are axially nested within the open ends of said U-shape facing each other.

8. The transformer defined in claim 1, wherein said primary coil is wound on a bobbin and the bobbin press fitted in an axial direction onto said stator.

9. The transformer defined in claim 1, wherein said secondary coil is wound on a bobbin and the bobbin press-fitted in an axial direction onto said rotor.

10. A transformer for transmitting electrical power across a rotary coupling comprising:
(a) a primary ferromagnetic member (102) having an annular configuration with a generally U-shaped configuration in radial section;
(b) a secondary ferromagnetic member (104) having an annular configuration with a generally U-shaped configuration in radial section, with the legs of said U-shape of said primary and secondary member interdigitated in an axial direction;
(c) a transformer primary coil (114) disposed on said annular primary member on one of the legs of said U-shaped configuration; and,
(d) a transformer secondary coil (116) disposed on said annular secondary member on one of the legs of said U-shaped configuration wherein said primary and secondary are disposed for relative rotation therebetween and adjacent legs of said U-shaped configurations define radial air gaps for magnetic flux.

11. The transformer defined in claim 10, wherein said secondary coil has four times the number of wound turns as said primary coil.

12. The transformer defined in claim 1, wherein said primary member and secondary member are formed of material having a saturation flux density of 0.2 Tesla and a relative magnetic permeability of at least 100 as compared to air.

13. A transformer for transmitting electrical power across rotary junction comprising:
(a) a primary member (102) formed of ferromagnetic material and having an annular configuration;
(b) a secondary member (104) of ferromagnetic material having an annular configuration; said secondary member disposed for relative rotation with respect to said primary member and said member having portions thereof interdigitated and defining a radial flux air gap therebetween;

(c) a primary coil (114) wound about said primary member;
(d) a secondary coil (116) wound about said secondary member and said secondary coil having at least three times the number of turns as said primary coil; and,
(e) said primary and secondary members and coils are configured to have a power density of at least 0.18 watts/CM^3 of ferromagnetic material of said primary and secondary members with a primary current frequency not greater than 2 kHz.

14. The transformer defined in claim 13, wherein at least one of said primary and secondary members is formed of material having a saturation flux density of 0.2 Tesla and a relative permeability of at least 100 compared to air.

15. The transformer defined in claim 13, wherein said secondary coil has four times the number of turns as said primary coil.

16. The transformer defined in claim 13, wherein said primary and secondary members have a generally U-shaped configuration in transverse section.

17. A transformer for transmitting electrical power across a rotary junction at fixed voltage comprising:
(a) a primary member (102) formed of ferromagnetic material and having an annular configuration;
(b) a secondary member (104) formed of ferromagnetic material and having an annular configuration and disposed for relative rotation with respect to said primary member, said primary and secondary members having portions thereof interdigitated and defining a radial flux air gap therebetween;
(c) a primary coil (114) wound about said primary member and said axis of rotation;
(d) a secondary coil (116) wound about said secondary member and said axis of rotation, and having at least 3.5 times the number of turns as said primary coil; and,
(e) said primary and secondary members and coils configured to give at least 0.2 Watts secondary output/Volt ampere primary input for a primary current frequency not greater than 2 kHz.

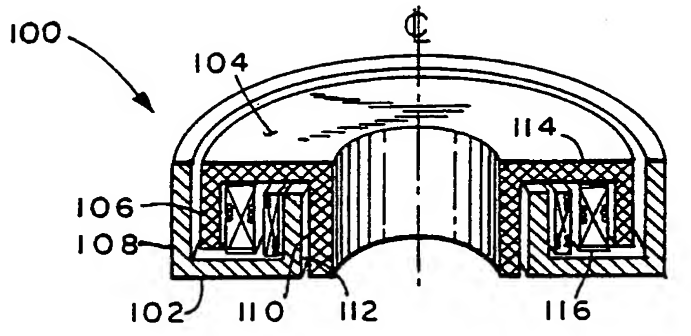

100
104
114
106
108
102
110
112
116

FIG. 1

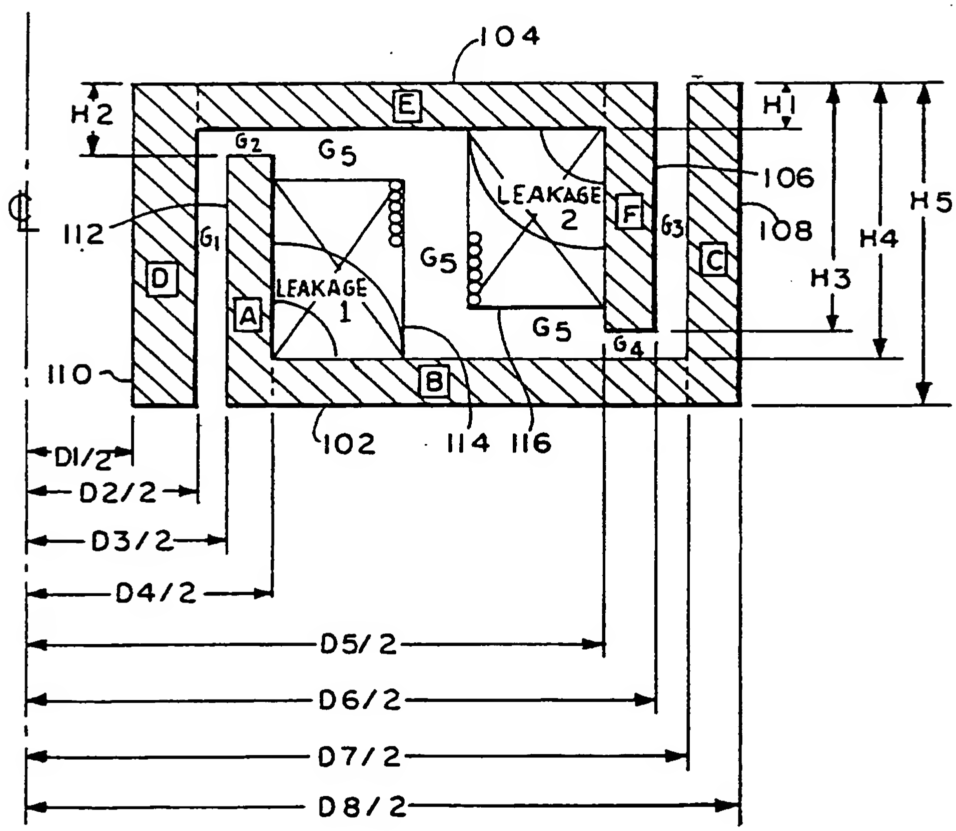

104
H2
H1
G2
G5
E
106
LEAKAGE
2
F
G3
108
H5
112
G1
G5
H4
D
LEAKAGE
1
A
C
H3
G5
G4
110
B
102
114
116
D1/2
D2/2
D3/2
D4/2
D5/2
D6/2
D7/2
D8/2

FIG. 2

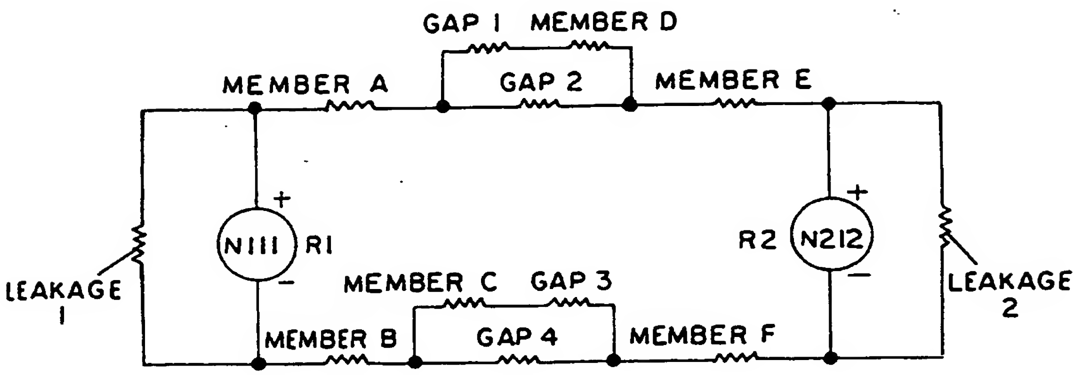


FIG. 3

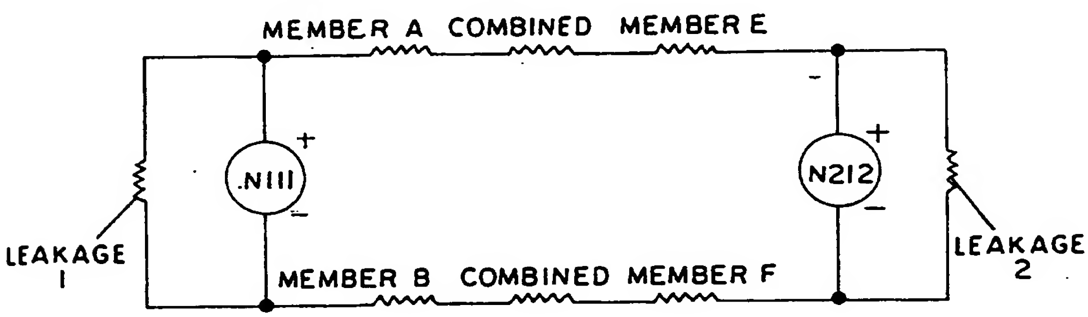


FIG. 4

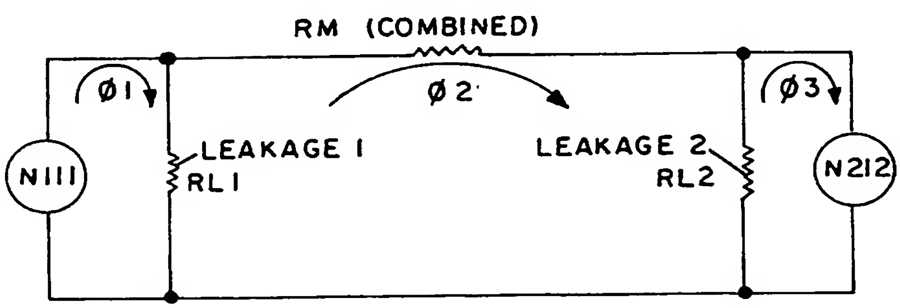


FIG. 5

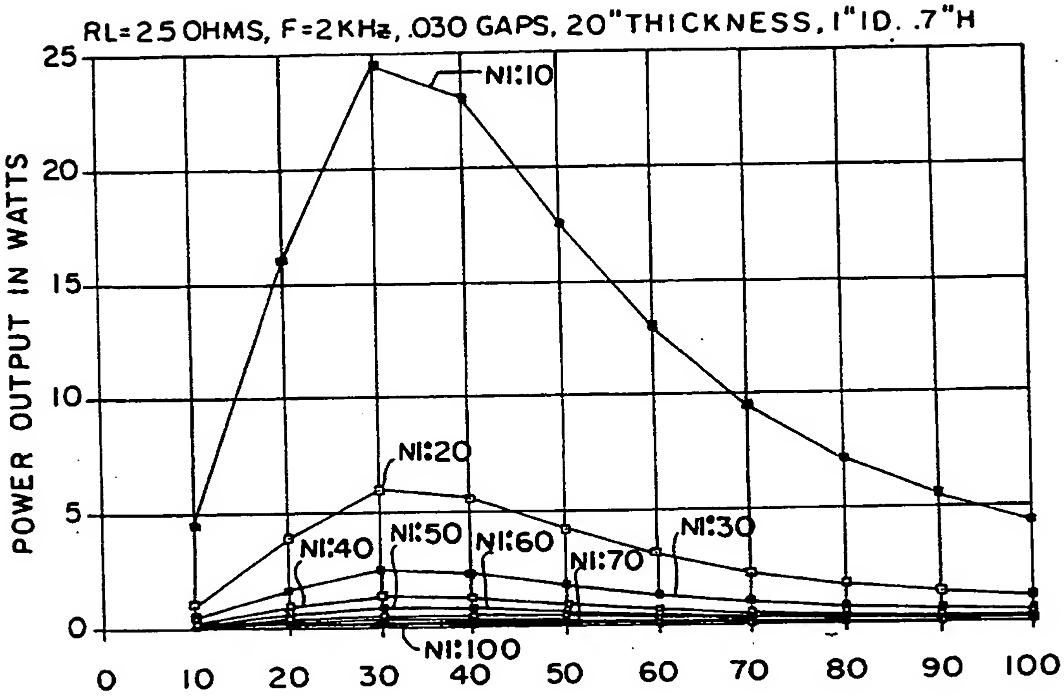

RL=2.5 OHMS, F=2KHz, .030 GAPS, 20"THICKNESS, 1"ID. .7"H
POWER OUTPUT IN WATTS
25
20
15
10
5
0
NI:10
NI:20
NI:30
NI:40
NI:50
NI:60
NI:70
NI:100
0
10
20
30
40
50
60
70
80
90
100

FIG.6

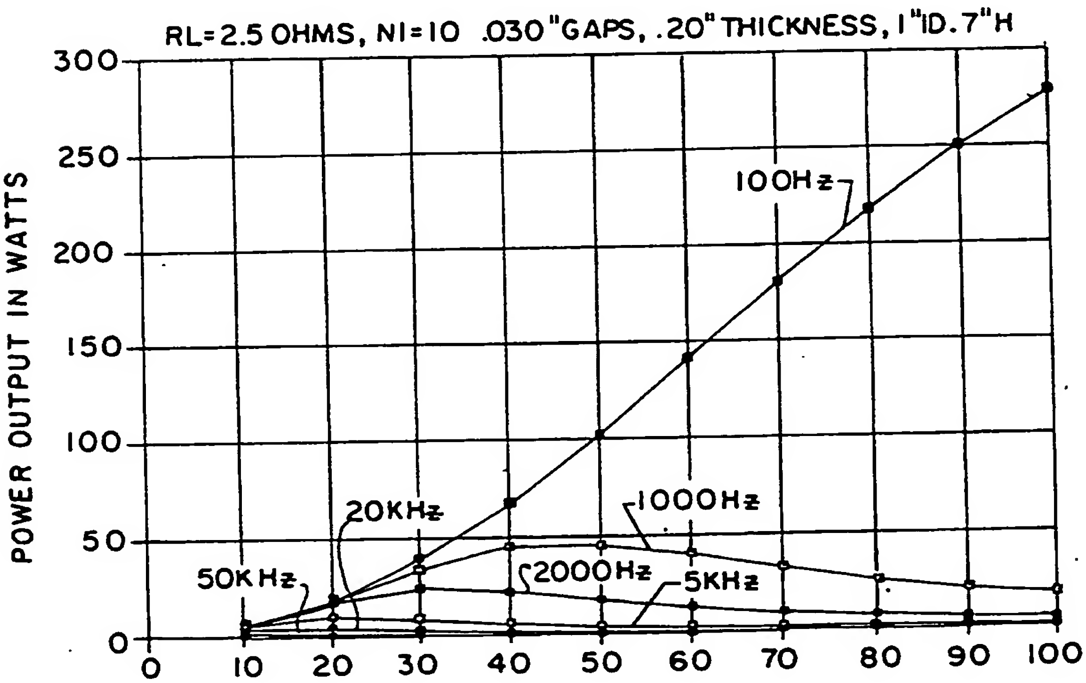

RL=2.5 OHMS, NI=10 .030"GAPS, .20"THICKNESS, 1"ID.7"H
POWER OUTPUT IN WATTS
300
250
200
150
100
50
0
100Hz
1000Hz
20KHz
50KHz
2000Hz
5KHz
0
10
20
30
40
50
60
70
80
90
100

FIG.7

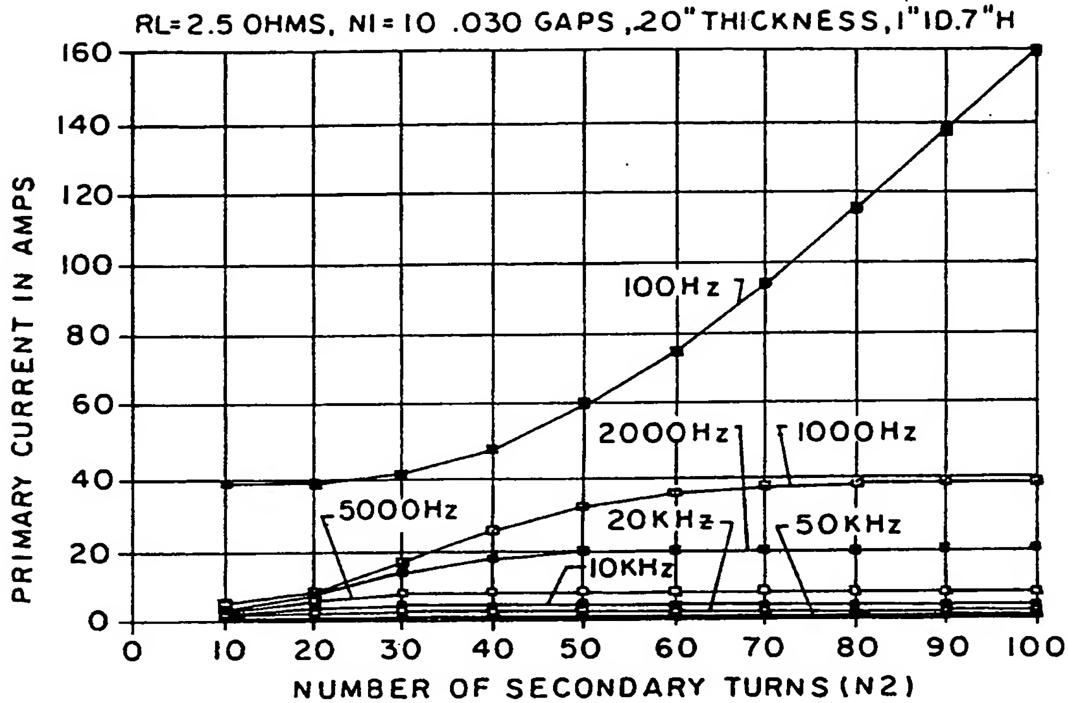

RL=2.5 OHMS, NI=10 .030 GAPS, .20" THICKNESS, 1" ID .7" H
PRIMARY CURRENT IN AMPS
NUMBER OF SECONDARY TURNS (N2)
100Hz
2000Hz
1000Hz
5000Hz
20KHz
50KHz
10KHz
0
20
40
60
80
100
120
140
160
10
30
50
70
90

FIG.8

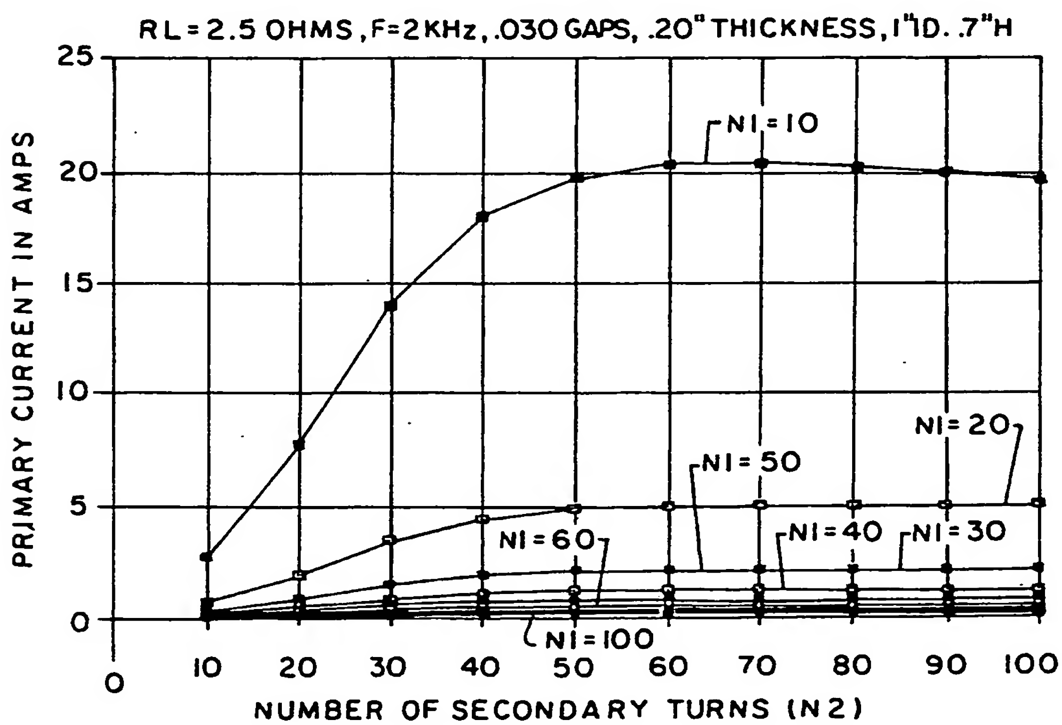

RL=2.5 OHMS, F=2KHz, .030 GAPS, .20" THICKNESS, 1" ID .7" H
PRIMARY CURRENT IN AMPS
NUMBER OF SECONDARY TURNS (N2)
NI=10
NI=20
NI=50
NI=60
NI=40
NI=30
NI=100
0
5
10
15
20
25
30
40
50
60
70
80
90
100

FIG. 9

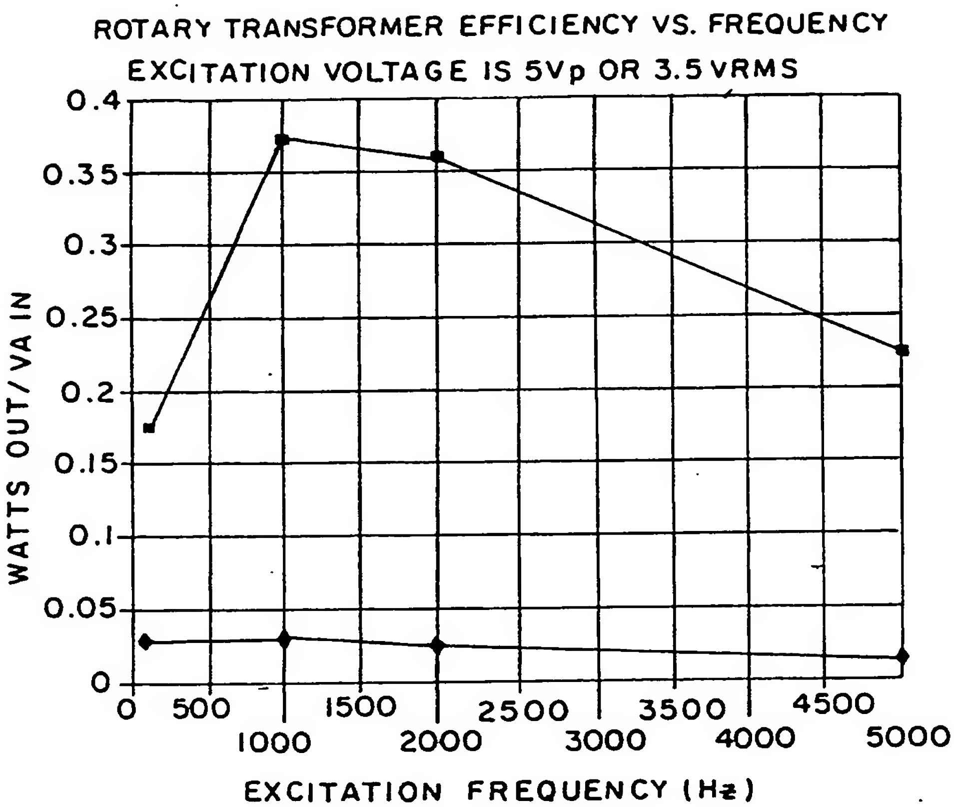
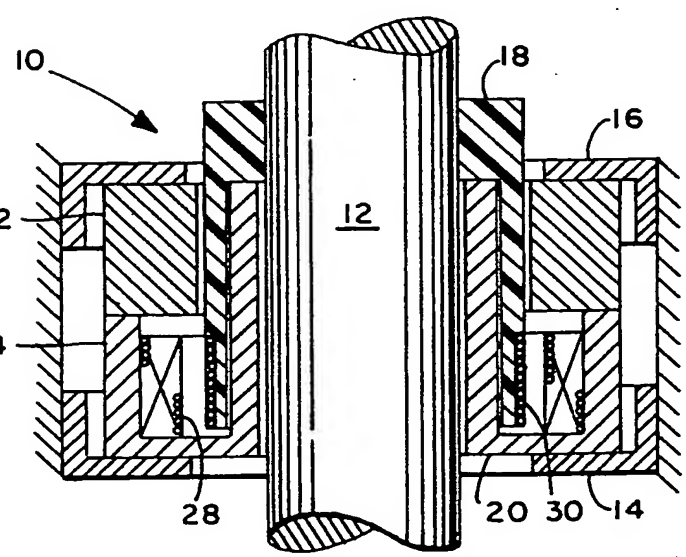
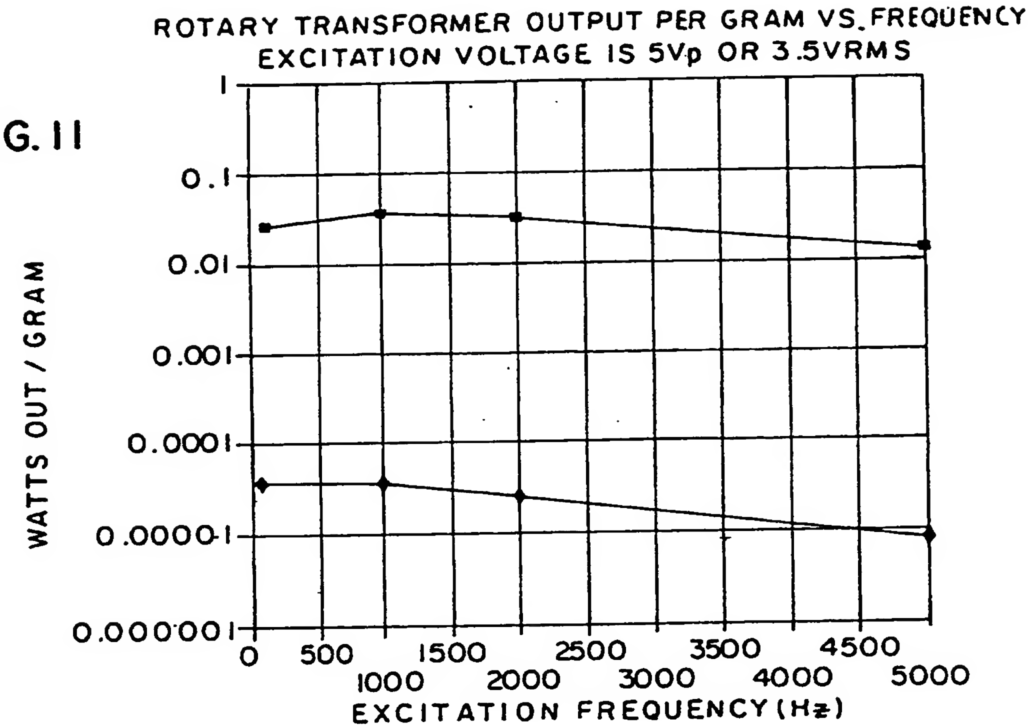


FIG.10



PRIOR ART
FIG.15

FIG. 11


ROTARY TRANSFORMER OUTPUT PER GRAM VS. FREQUENCY
EXCITATION VOLTAGE IS 5Vp OR 3.5VRMS
WATTS OUT / GRAM
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
EXCITATION FREQUENCY (Hz)

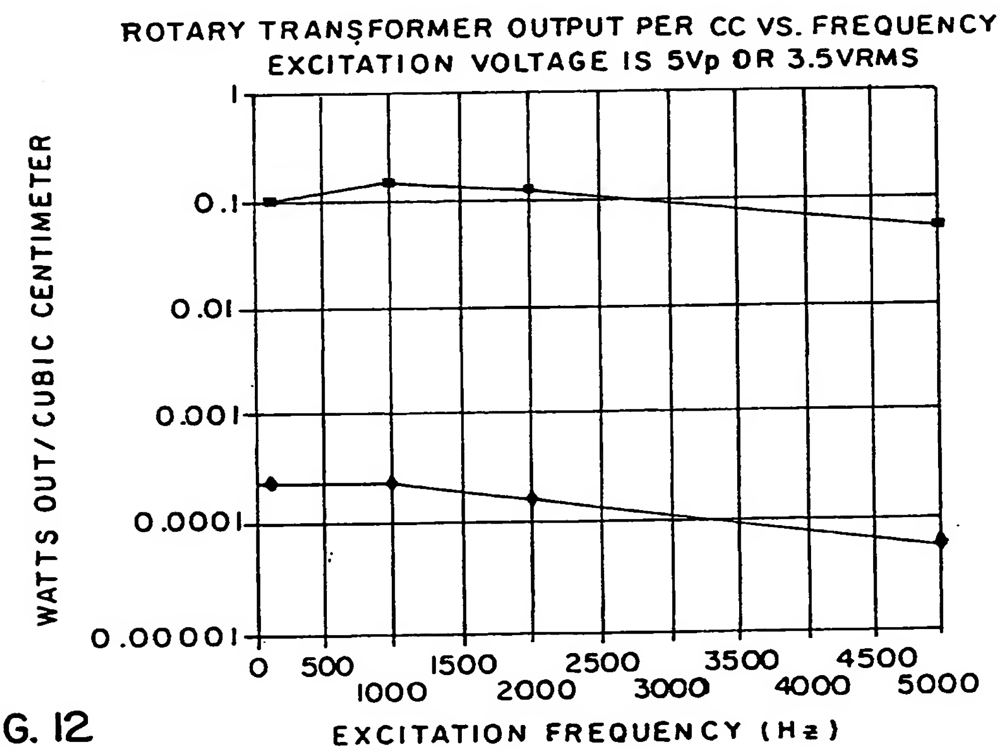

ROTARY TRANSFORMER OUTPUT PER CC VS. FREQUENCY
EXCITATION VOLTAGE IS 5Vp OR 3.5VRMS
WATTS OUT/ CUBIC CENTIMETER
1
0.1
0.01
0.001
0.0001
0.00001
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
EXCITATION FREQUENCY (Hz)

FIG. 12

FIG.13

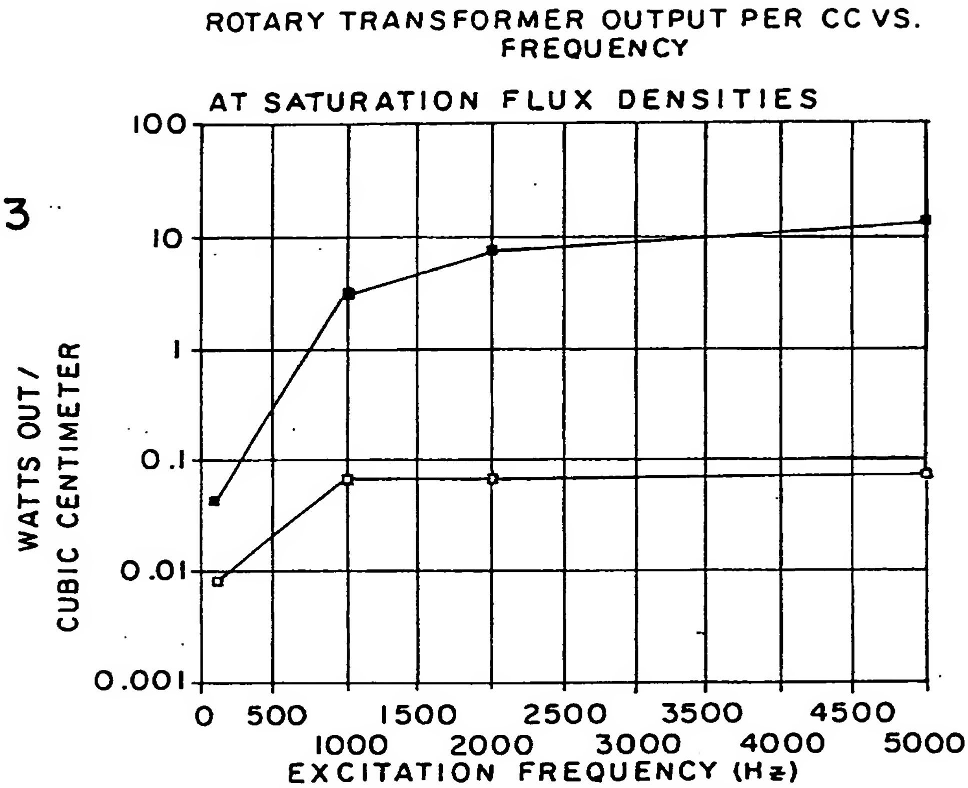
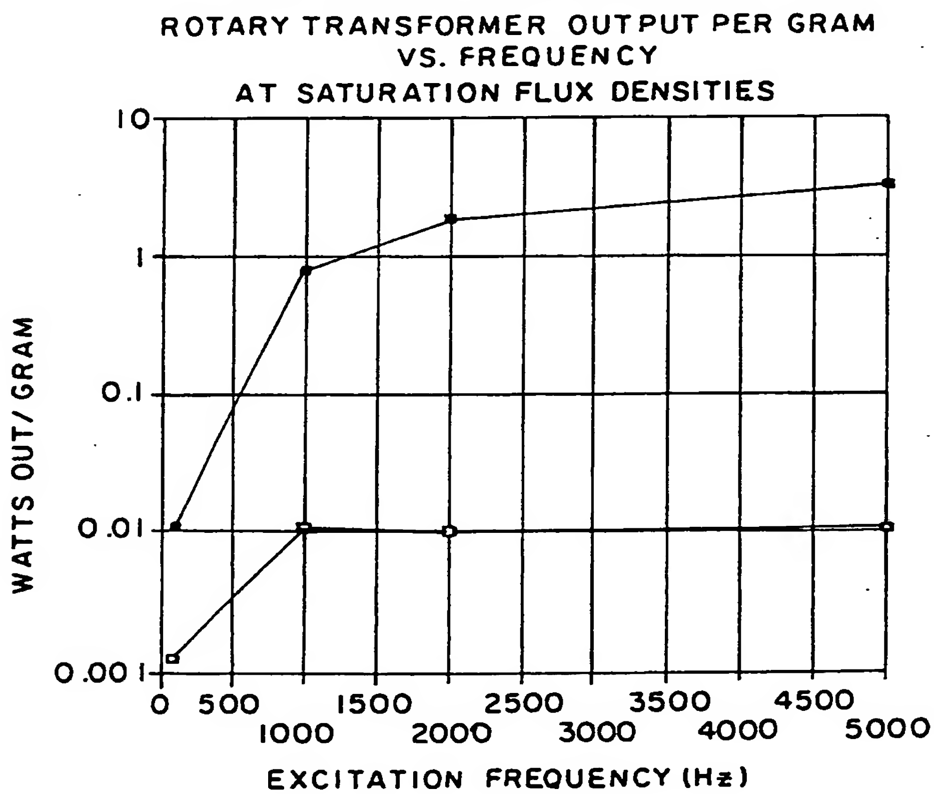

ROTARY TRANSFORMER OUTPUT PER CC VS. FREQUENCY
AT SATURATION FLUX DENSITIES
100
10
1
0.1
0.01
0.001
WATTS OUT/ CUBIC CENTIMETER
0 500 1500 2500 3500 4500
1000 2000 3000 4000 5000
EXCITATION FREQUENCY (Hz)

FIG.14


ROTARY TRANSFORMER OUTPUT PER GRAM VS. FREQUENCY
AT SATURATION FLUX DENSITIES
10
1
0.1
0.01
0.001
WATTS OUT/ GRAM
0 500 1500 2500 3500 4500
1000 2000 3000 4000 5000
EXCITATION FREQUENCY (Hz)

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 95 10 5433

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
Y	FR-A-2 552 260 (EREVANSKY POLITEKHN INSTI) 22 March 1985	1	H01F38/18
	* figure 1 *		
A		7	
Y	DE-C-39 15 188 (DAIMLER-BENZ) 22 November 1990	1	
	* figure 9 *		
A		2,3	
A	US-A-2 432 982 (SPERRY GYROSCOPE COMPANY) 23 December 1947		
A	FR-A-1 595 881 (BROWN BOVERI) 15 June 1970		

TECHNICAL FIELDS SEARCHED (Int.Cl.6)

H01F
G08C

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	25 July 1995	Vanhulle, R

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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